Biodiversity climate change impacts report card technical paper

13. Overview of climate change implications for ecosystem services in the UK

Nathalie Doswald & Cordula Epple
UNEP World Conservation Monitoring Centre
219 Huntingdon Road
Cambridge, CB3 0DL, UK

Email: Nathalie.Doswald@unep-wcmc.org; cordula.epple@unep-wcmc.org

With thanks for comments and input to Lera Miles and Claire Brown (UNEP-WCMC), Pam Berry (ECI), Ruth Waters and Mike Morecroft (Natural England).Authors:

Summary of main findings*

- Information on the impacts of climate change on ecosystem services is sparse compared to information about impacts on species. The nature of the link between biodiversity and ecosystem services is complex, making it difficult to draw direct conclusions about impacts on ecosystem services from knowledge on changes in biodiversity.[1]

- Supporting services are likely to be impacted by climate change because climate has a strong influence on many ecosystem processes,[2] though in many cases how this translates to changes in the delivery of the service is insufficiently known.
    - Changes in temperature and moisture affect soil processes, including carbon and nutrient cycling.[1] Although experiments and observations have helped to elucidate some aspects of the mechanisms that govern these impacts, there are complex interrelationships and feedbacks, and much more research is required in order to allow for solid projections of outcomes.

- Changes in mean climate will affect the magnitude of the supply of regulating services, but extreme climatic events that lead to sudden shifts in the characteristics of land cover are more of a threat to these services.[1] At the same time, regulating services can help to buffer the impacts of extreme events on people.[2]
    - Carbon sequestration is likely to be enhanced in some areas in the short term due to increased productivity, but may decrease in the longer term, with changes to biomass cover and soil properties determining the magnitude of change[3]. Extreme events, such as persistent drought and fire, and to a lesser degree flooding, can be highly detrimental to carbon storage and sequestration especially on peatlands.[1]
    - Although more research is required, it is clear that the water cycle and water-related services are and will be affected in some areas with consequences for people.[2] The importance of ecosystem processes that improve water quality will increase, as more frequent periods of high and low flow[2] will lead to increased concentrations of some nutrients and contaminants.[2]
    - Flood and erosion control services will be more tested in the future due to increases in frequency and intensity of extreme events[2], which may surpass the threshold of service supply.[4] Changes in climate are also likely to impact (either positively or negatively) on the ecosystem structure and composition providing the services.[4] Services are likely to be significantly reduced especially where ecosystems are already degraded.[2] Nevertheless land use change and degradation are more immediate threats that climate change may exacerbate.[1]
    - Evidence shows that climate change can impact on host-pollinator interactions.[1] Pollinators are under stress from a number of pressures including climate change, land use change, pests and diseases and invasive species, which may reinforce each other[1], making it difficult to attribute observed changes to a single cause. Population declines, changes in distribution and mismatches in phenology of host plants and pollinators have been evidenced and future climate change is likely to contribute to a continuation of this trend.[2] However, major disruption in pollination services is unlikely so long as a diversity of pollinators is maintained, because pollination networks typically involve multiple species interactions which are relatively resilient.[2]

* Certainty terms are put on each of the key findings (see Annex). 1 = Well established; 2 = Established but incomplete evidence; 3 = Competing explanations; 4 = Speculative

  - Although other factors than climate change are involved, there is some evidence that pest and disease control services are being affected in the UK by climate change; pests and diseases are spreading[2], which may lead to increased demand for the ecosystem service[2] as well as decreased supply due to temporary or permanent shifts in the balance between pathogens and pests and their antagonists[4]; the trend towards increased occurrence of pests and diseases is likely to continue.[4]

- Provisioning services are intensively managed in the UK and are affected more by land use decisions than environmental parameters. Nevertheless climate change does affect the magnitude and frequency in service delivery. In particular, increasing extreme events and spread of pests and diseases due to climate change affect both agriculture and forestry in the UK.[2]

- Climate change impacts on cultural services depend on personal values and preferences. For the tourist trade in the UK, climate change may alter the value of different locations within the UK with a northwards shift in choice of destination and greater number of domestic holidays[4]. Changes in wild species populations due to climate change may impact recreational activities, such as bird watching or grouse shooting.[4]

- It seems from the review of the literature that land use change, land degradation, and other socio-economic drivers currently have a stronger effect on ecosystem services than mean climate change in any given location.[2] This observation seems to confirm the potential for adapting to climate change through sustainable land use interventions[4]. However, over the long term the effects of changes in mean climate are expected to become more pronounced and surprises in the responses and interactions of organisms and ecosystems are likely[4].

- Extreme climatic events on the other hand are a more immediate threat to the provision of many ecosystem services but information is limited with regard to their future frequency and intensity. Long-term climate data suggests that there has already been some increase in the frequency of heavy rainfall events in the UK, and this trend is expected to continue.[2] The expectation of more frequent summer droughts is not yet confirmed by observation.[2] More research into projections of extreme events and their short-term and long-term effects on ecosystem processes and services is necessary for managing climate change impacts.

Introduction

UK ecosystems and their biodiversity provide services that are crucial and beneficial to the human population. The UK National Ecosystem Assessment (UK NEA 2011a) gave a first overview of the state and trends of biodiversity and ecosystem services in the United Kingdom. It indicates that while provision of some services has been maintained, many others have declined in the past 60 years through habitat loss and degradation and changes in biodiversity. Climate change has not been a main driver in these changes in the past except in marine and coastal areas and mountains, moorland and heaths; but it is expected to play an increasing role.

Whilst much has been reported on the impacts of climate change on (components of) biodiversity, there have been comparatively few reports on impacts on ecosystem services. This may largely be due to the focus of established monitoring systems and the availability of long-term observational datasets (many of which are focused on the distribution and abundance of species and habitats rather than functional traits of ecosystems), and a lack of ecosystem service indicators.

The Millennium Ecosystem Assessment (MA 2005) describes four main types of ecosystem services: supporting, regulating, provisioning and cultural. The UK NEA further refined the MA framework to a logical flow where 'ecosystem processes and intermediate services' underpin a set of 'final ecosystem services' that directly contribute to 'goods' that people value (Figure 1).

Ecosystem processes/intermediate services		Final ecosystem services (*example of goods*)	
Supporting services	• Primary production • Soil formation • Nutrient cycling • Water cycling	**Provisioning services**	• Crops, livestock, fish (*food*) • Trees, standing vegetation, peat (*fibre, energy, carbon sequestration*) • Water supply (*domestic and industrial water*) • Wild species diversity (*bioprospecting, medicinal plants*)
• Decomposition • Weathering • Climate regulation • Pollination • Disease and pest regulation • Ecological interactions • Evolutionary processes • Wild species diversity		**Cultural services**	• Wild species diversity (*recreation*) • Environmental settings (*recreation, tourism, spiritual/religious*)
		Regulating services	• Climate regulation (*equable climate*) • Pollination • Detoxification and purification in soils, air and water (*pollution control*) • Hazard regulation (*erosion control, flood control*) • Noise regulation (*noise control*) • Disease and pest regulation (*disease and pest control*)

***Figure 1**: Ecosystem services in the UK NEA classified according to both ecosystem service type (provisioning, regulating, cultural and supporting) and whether or not they are final ecosystem services or intermediate services and/or processes. For each final ecosystem service an example of the good(s) it delivers is provided in italics. Source: Table 2.2, Chapter 2 Conceptual Framework and Methodology, UK NEA (2011b).*

Impacts of climate change on ecosystem services can be a consequence of changes in both the abiotic and the biotic components of ecosystems due to alterations in temperature, precipitation and atmospheric chemistry. Climate change impacts on biodiversity that could affect ecosystem service provision include species turnover and associated increases or decreases in overall species diversity, as species expand or contract their ranges in response to climate change; metabolic changes affecting physiology, phenology and population dynamics, which can scale up to affect ecosystem processes and potentially services; and changes in species interactions due to shifts in community composition (Montoya & Raffaelli 2010). Ecosystem services at the local level are likely to be affected most significantly if they have a strong relationship with individual species that are either already present and undergoing substantial changes, or newly arriving in the area.

However, while some ecosystem services are directly linked to the presence and condition of particular species or habitat types (e.g. certain aesthetic, cultural and recreational services), in most cases the relationship between elements of biodiversity and the provision of ecosystem services is more complex[†]. Often, ecosystem services depend more on the presence of functional groups of species (such as trees, peat-forming mosses, insectivore birds, pollinators or litter-decomposing arthropods) than on individual species. This is particularly true in the case of supporting and regulating services.

The degree to which the diversity of species assemblages in an ecosystem or within a functional group contributes to the extent or reliability of service provision has been a matter of some debate (Kremen 2005; Balvanera et al. 2006; Bennett et al. 2009; Mooney et al. 2009; Montoya & Raffaelli 2010). There is evidence to suggest that higher levels of biodiversity often have a positive effect on service provision, however there is no fixed or linear relationship between biodiversity and the

[†] Note also that some authors consider the 'hosting' of biodiversity to be an ecosystem service in itself; this perspective is especially relevant in situations where biodiversity is seen as a resource, e.g. because it provides a pool of genetic material that can be used in plant breeding, or a basis for ecological or pharmaceutical research (cp. Mace et al. 2012).

intensity of the ecosystem processes that result in service provision (e.g. vegetation composed of few species may have a similar or higher rate of primary production than a more diverse one) (Montoya & Raffaelli 2010; Isbell et al. 2011; Norris et al. 2011).

A main consideration that has been raised in the context of climate change is that functional redundancy (i.e. the presence of numerous species that can fulfill the same function) may increase the resilience of ecosystems to disturbance (Elmqvist et al. 2003; Thompson et al. 2009; Miles et al. 2010), thus reducing vulnerability to potential negative impacts from climate change.

A recent comprehensive review of the current knowledge on the relationship between biodiversity and ecosystem functioning and services has concluded among other things that 1) there is now good evidence to support the hypothesis that biodiversity is crucial for ecosystem efficiency with regard to certain functions (e.g. biomass production, nutrient capture, decomposition) and the stability of these ecosystem functions through time; 2) loss of biodiversity can erode ecosystem function across different trophic levels and scales; and 3) for many types of ecosystem services, knowledge on the nature of the relationship between biodiversity and service provision is still insufficient to make general statements, and in some cases there is conflicting evidence (Cardinale et al. 2012).

Using information about the impacts of climate change on biodiversity in the UK to draw conclusions about consequences for ecosystem services is thus difficult, and more observational evidence on the way in which climate change affects biodiversity and ecosystem services in specific settings is needed. Obtaining such evidence is complicated further by the influence of other drivers of change, such as changes in land use, pollution or species invasions. Despite the gaps in knowledge with regard to the links between biodiversity and ecosystem services, it is widely accepted that biodiversity conservation will be crucial for preserving ecosystem services in the long-term (Cardinale et al. 2012, Hicks et al. 2014, Isbell et al. 2011, Mace et al. 2012).

Focus of the present document

Drawing on existing information from the work undertaken by the UK National Ecosystem Assessment and on other recent literature, this paper examines the implications that climate change has for the delivery of ecosystem services in the UK. Given the many interactions between climate, land use and the state of ecosystems, such an assessment also needs to take account of the possible trends in socio-economic drivers of change as exemplified by the UK NEA scenarios (see Box 1). The paper focuses on implications for ecosystem services for which the UK population are direct beneficiaries and/or that have a strong link with biodiversity conservation.

Following the framework provided by the UK NEA, the following ecosystem service categories were selected:

- **Supporting**: soil formation and nutrient cycling;
- **Regulating**: carbon sequestration; regulation of water quality and water flows; hazard regulation (flood and erosion control); pollination; pest and disease control
- **Provisioning**: supply of products from agriculture and forestry
- **Cultural**: availability of environmental settings and wild species.

Changes due to climate change in the supporting service of primary production are not directly covered but are mentioned in the context of regulating and provisioning services.

UK biodiversity and ecosystem services

The UK has comprehensive data on biodiversity, and the UK NEA endeavoured to establish the importance of a range of species groups in underpinning final ecosystem services (Figure 2); though this assessment was conducted using expert opinion due to a lack of objective information

(Norris et al. 2011). An understanding of which species are important for different services is useful for considering the effects of climate change on ecosystem services through examining the effects of climate change on species, populations and communities. However, the results of the assessment also highlight the knowledge gaps.

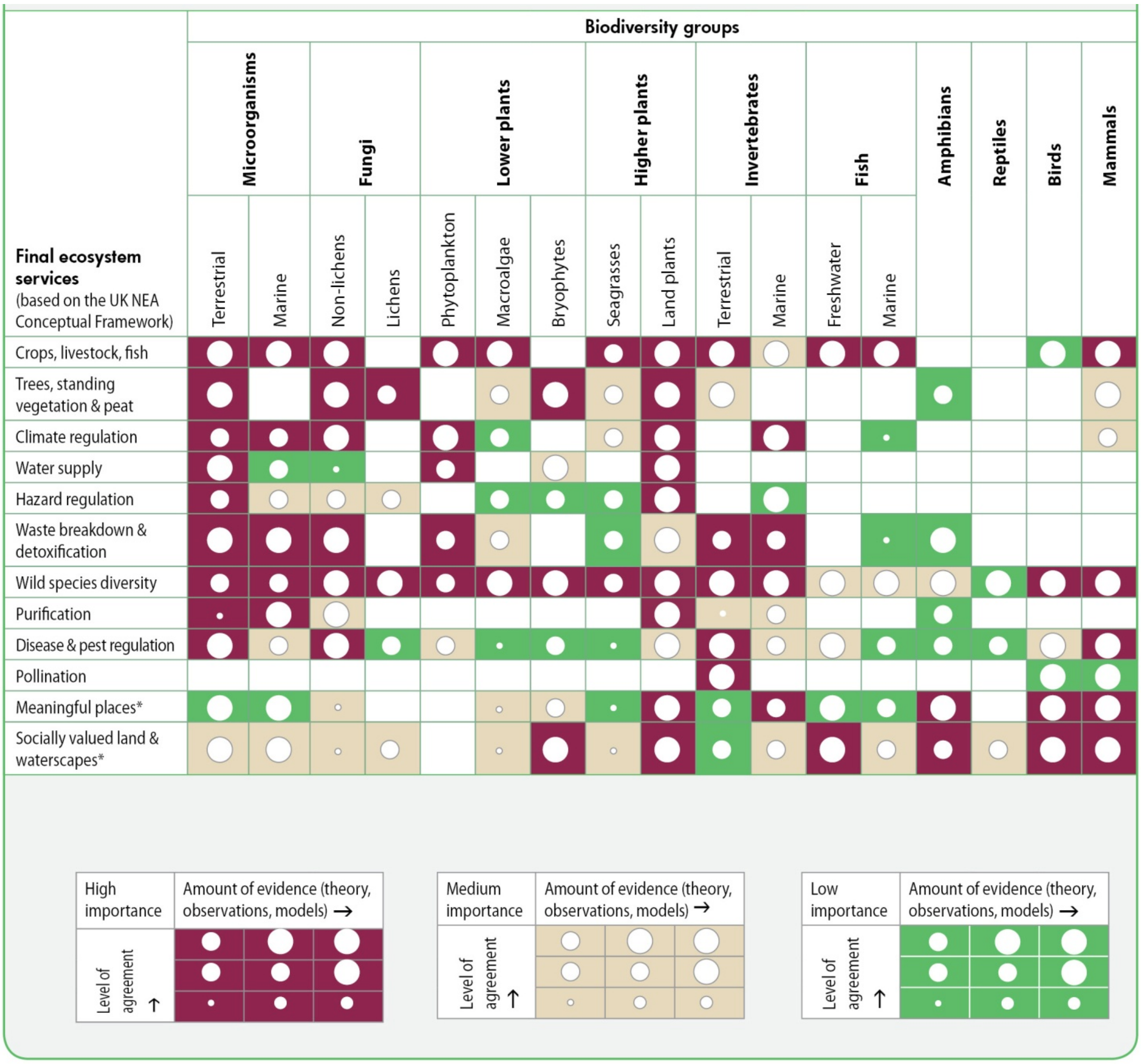


Figure 2: *The importance of different species groups in underpinning final ecosystem services based on expert opinion. Importance is colour-coded: high (maroon), medium (beige), low (green), unimportant on the basis of available evidence (blank). The size of the circle in each cell is used to illustrate the level of uncertainty in the available evidence. Source: Table 4.2, Chapter 4 Biodiversity in the Context of Ecosystem Services, UK NEA (2011b). *Note: For the purposes of the Cultural Services chapter (Chapter 16), Cultural services have been combined into 'environmental settings'.*

Box 1 UK NEA scenarios

The UK NEA (2011b) has produced future scenarios of land cover for the UK as a basis for analyzing the possible changes in biodiversity and ecosystem services in the UK over the next 50 years. These scenarios can help to explore the interactions between climatic and non-climatic drivers of change. They take into account previous scenario work, for example under UKCIP (Hulme et al. 2002) and FORESIGHT Land Use Futures (FLUF 2010). There are six scenarios for 2060 covering a suite of storylines which vary according to prevailing socio-economic priorities. The factors assumed to affect land cover as included in the scenarios are altitude, woodland potential, urban influence, landscape designation, agricultural land classification, change in temperature, change in precipitation, inland flood risk and change in sea level (see Haines-Young et al. 2011). The outcomes of each of the scenarios are provided for both high and low climate change projections.

Climate change impact on supporting services

Supporting services are directly related to ecosystem functioning. Understanding the impact that climate change can have on these services is a crucial basis for understanding its implications for ecosystems and the species they support. However, the link between ecosystem functioning and the benefits that supporting services provide to people is rarely made in the literature and is thus often not directly examined in discussions on ecosystem services.

Soil formation and nutrient cycling

The formation of soils is influenced by the substrate, topography, climate, the activity of living organisms and time. Climate change influences the development and state of soil through changes in temperature and precipitation, with concomitant changes in parameters such as frost occurrence, water saturation and aeration, as well as through extreme events that can lead to increased soil erosion (de Vries and Bardgett 2015, see also section on regulating services). Climate change further affects soil through its direct impact on the organisms that live in and above it, especially plants and litter decomposers. Some changes in the composition and functional characteristics of soil organism communities are also triggered by rising atmospheric concentrations of carbon dioxide (de Vries and Bardgett 2015).

One of the main characteristics of soils that will be influenced by climate change is their content of organic matter. This will in turn affect important soil properties such as aggregate structure and stability, water holding capacity, cation exchange capacity, soil nutrient content and ultimately the capacity to support agricultural or silvicultural production.

Many of the mechanisms that will determine the direction and magnitude of climate change impacts on soils are as yet poorly understood (Brevik 2013). This is partly due to the comparatively small amount of research that has focussed on belowground processes and environmental change (Pritchard 2011), as well as the large number of variables (including soil moisture content, temperature, organic matter content and nutrient status) and the complex interactions and feedback loops that are involved.

A number of important soil processes such as nitrogen mineralisation, litter decomposition and soil respiration are dependent on the community composition, abundance and metabolic rates of soil organisms, which are directly influenced by the prevailing climate (Waldrop & Firestone 2006, de Vries and Bardgett 2015). The diversity of species and their functional redundancy, as well as turnover under climatic change, may have an influence on the degree to which changes to soil processes are buffered (Pritchard 2011).

The findings of experimental studies on the effects of alterations in temperature and precipitation in different ecosystems suggest that impacts on ecosystem function vary strongly between different settings (Emmett et al. 2004; Blankinship et al. 2011). For some soil processes, even the overall direction of change remains a matter of debate.

For example, higher soil temperatures will stimulate litter decomposition and chemical weathering, both of which could lead to higher nutrient availability. At the same time, there is evidence that rising CO_2 concentrations can stimulate plant growth through the so-called CO_2–fertilization effect, but may also increase the ratio of carbon to nitrogen in biomass, leading to reduced mineralization rates and lower levels of plant-available nitrogen, which in turn could limit plant growth (Ciais et al. 2014). In addition, increases in rainfall could lead to intensified leaching of nutrients from the soil (Bardgett et al. 2008; Blume 2011; Brevik 2013).

To what degree soils are affected by climate change will depend on both their exposure and sensitivity to climatic stimuli. Greater impact is likely to occur in areas where large climatic changes are expected and where climatic conditions currently constrain soil organisms, e.g. at high altitudes and/or latitudes. In these areas, the rate of soil processes such as decomposition and mineralisation is likely to be noticeably increased, while the magnitude of change will also depend on the availability of nutrients from litter and on the effects of climate change on vegetation (Anderson 1991; Coûteaux et al. 1995; Kirschbaum 1995; Kardol et al. 2010). The impact of aboveground climatic changes on the microclimate within the soil further depends on the nature of the soil, e.g. porosity and organic matter content (Anderson 1991; Davidson & Janssens 2006). In the UK, montane soils and peatlands are considered most at risk of degradation due to climate change (Bardgett et al. 2011).

Climate change impact on regulating services

Regulating services are diverse and emanate from a number of characteristics of a functioning ecosystem. For example, structural components of an ecosystem can contribute to hazard control (e.g. roots and above-ground biomass reduce erosion), biochemical cycles contribute to regulating the climate (e.g. plants take up carbon and release oxygen), and ecological interactions contribute to maintaining the ecosystem in the long term (e.g. insects pollinate plants, allowing them to reproduce). Thus relationships between regulating services and biodiversity, and in particular specific species, are varied. For instance, pollination is often a species-specific service (i.e. many plants are pollinated by a certain group of arthropod species) while climate regulation and hazard control are linked to larger taxonomic groups (e.g. higher plants are important).

It has been suggested that consistency in regulating services is a good indicator of ecosystem resilience, a property which is important to cope with pressures such as climate change (Bennett et al. 2005; Bennett et al. 2009).

The UK NEA (2011b) future scenarios (see box 1) project either increases or decreases in overall regulation services, depending on the storyline. Under the different scenarios, change in regulation services as compared to the present is described as being in the order of -50% to +10%. The difference in impacts between the high and low climate change projections is estimated to be in the order of 1% under all scenarios. These scenarios do not distinguish different regulating services, and climate change is portrayed through changes in mean temperature and precipitation. This could suggest that changes in mean climate would be a minor driver of change in regulating services over the whole of the UK compared with other factors. However, climate change entails more than changes in mean climate values. Moreover, the summarized result may hide potential changes to different aspects of regulating services or at different locations within the UK.

Carbon sequestration

Climate, soil substrate, topography and latitude are the main abiotic factors that determine the amount of carbon in a given area through time, while physiological characteristics of individual species and community composition are relevant parameters on the biotic side. The uptake and sequestration of carbon by plants, as well as the release of carbon through animal, plant and microbial respiration, are governed by ecophysiological processes that are highly sensitive to changes in climate. Organic carbon is stored in soils and in biomass and these elements of ecosystems are thus sinks for greenhouse gases. Various processes, including land use change and ecosystem degradation, can cause these sinks to become sources of carbon dioxide. Ecosystem management plays a large role in either promoting or reducing carbon storage, and certain management practices can instigate carbon losses (Worrall et al. 2011; Alonso et al. 2012). There is some evidence that higher levels of plant biodiversity may improve the resilience of carbon stocks to climate change (Miles et al. 2010).

According to dynamic global vegetation models and more recent earth system models, and corroborated by observational evidence and experimental studies, terrestrial ecosystems are likely to continue to absorb more carbon than they emit over the short to medium term at the global scale. This is due to the fact that large terrestrial areas could benefit from a longer growing season, increasing precipitation, and carbon dioxide fertilisation effects including enhanced water use efficiency (Cao & Woodward 1998; Ciais et al. 2005; Boisvenue & Running 2006; IPCC 2007; Zhao & Running 2010; IPCC 2013). However, a reversal may occur in the future as these responses reach saturation and nutrient availability becomes a limiting factor for further carbon uptake, while higher temperatures increase both respiration and evapotranspiration, and carbon release through extreme events as well as continued emissions from land use change offset some of the carbon gains (IPCC 2007; Heimann & Reichstein 2008; Chapmann et al. 2009; Pussinen et al. 2009; McCarthy et al. 2010; Worrall et al. 2011; Ge et al. 2012; IPCC 2013). In view of the large spread of model results and incomplete process representation (e.g. none of the available models account for decomposition of carbon in permafrost), there is currently considered to be low confidence in the magnitude of modelled future terrestrial carbon changes at the global level (IPCC 2013).

It has been estimated that UK soils store nearly 10 billion tonnes of carbon (Dawson & Smith 2007), while UK live biomass stores approximately 118 million tonnes of carbon (Ostle et al. 2009). Over half of the UK's soil organic carbon occurs in peat soils, predominantly in Scotland and Wales, while much of the carbon stored in live biomass is concentrated in forests. It is reported that overall, UK ecosystems have been a net sink of carbon dioxide since 1990, though cropland areas are considered to be net sources (Jackson et al. 2009; MacCarthy et al. 2010). In 2012, forests in England are estimated to have removed an equivalent of 5.4 million tonnes of CO_2 from the atmosphere (Defra 2014, based on data from the LULUCF greenhouse gas inventory[‡]).

Both the National Soil Inventory (Cranfield University 2013) and the Countryside Survey for England (Carey et al. 2008) have reported significant carbon losses from arable and horticultural soils in England in recent decades, while there is disagreement between the two datasets over the trend in carbon content across all types of soils (Adaptation Sub-Committee 2013). Large impacts of land use on soil carbon contents have also been reported from Scotland, where estimates of annual changes in soil carbon contents suggest that more than 800,000 t of carbon have been lost each year between 1990 and 2009. A statistical analysis of the data, which was derived from the National Soils Inventory of Scotland, suggests that these changes have been driven by land use change more than by changes in climate (Smith et al. 2009).

[‡] Note that in 2015, changes to some elements of the LULUCF greenhouse gas inventory are planned, taking into account new input data from the National Forest Inventory.

While land use is considered to be the main cause of observed soil degradation and there is conflicting evidence about the extent of a climate signal in past carbon emissions from UK soils (e.g. Sowerby et al. 2008; Smith et al. 2009), there is concern that prevailing levels of degradation may increase the vulnerability of ecosystem carbon stocks to future climate change, especially in peatlands (Chapman et al. 2009; Worrall et al. 2011). For example, the major part of the area of upland deep peat in England, where an estimated 140 million tonnes of carbon are stored (Natural England 2010), is currently considered to be in a degraded state that leads to carbon emissions and no longer allows peat-forming vegetation to develop. The extensive lowland fen areas of East Anglia have been identified as another potential hotspot of soil carbon loss (Adaptation Sub-Committee 2013).

Impacts of climate change on peatland carbon stocks could also result from extreme events such as persistent drought and fire (Albertson et al. 2010; Fenner & Freeman 2011; JNCC 2011). Experiments in the UK have shown that persistent drought increased soil respiration flux in carbon-rich soils (Sowerby et al. 2008), and fires on drained peat soils have been problematic in the past (JNCC 2011).

Although the majority of wildfires are started by humans, either accidentally or deliberately, climate change may increase the likelihood of their occurrence in the UK (IPCC 2014). This may also threaten carbon stores in forests and woodlands. The UK Climate Change Risk Assessment suggests that the existing low wildfire risk could increase by between 10 and 50% by the 2080s (HR Wallingford 2012).

Other threats to forest carbon stocks caused by climate change could result from increases in the occurrence of storm and insect pest damage (see also the sections on pest and disease regulation and provisioning services).

Regulation of water quality

Ecosystems have an important function in the water cycle, as vegetation and soils have an influence on different processes such as the capture of water, infiltration, storage, runoff and evapotranspiration (Finch 2000; Huxman et al. 2005). Feedbacks exist between the impact of climate change on vegetation and vice versa (Gerten et al. 2004). As water passes through ecosystems, dissolved substances can be removed through adsorption or decomposition. Changes in ecosystems can thus have significant impacts on water quality (Delpla et al. 2009).

The regulation of water quality is a typical example of an ecosystem service that will be affected by the impacts of climate change on ecosystems, and may at the same time become more valuable to people, if climate change leads to deterioration in water quality.

It is expected that climate change will affect water quality in several ways (IPCC 2014): Shallow water bodies in particular may experience rapid temperature increases during periods of hot weather, which can lead to oxygen depletion and algal blooms. Periods of drought may also lead to low flows that increase concentrations of biological and chemical contaminants in running waters, and enhance sedimentation in drainage systems. Heavy rainfall events on the other hand can cause increased surface runoff, raising nutrient loadings in water bodies. Where high precipitation induces flooding, this can further lead to contamination of surface and coastal waters with sewage and/or chemicals (pesticides).

According to current projections, water quality in the UK is expected to decrease over the coming decades (UK NEA 2011; IPCC 2014). Ecosystems with important functions for the regulation of water quality should therefore be managed carefully. This is particularly true for peatlands in the upper reaches of rivers, which are subject to a variety of pressures (see preceding section) and at the same time function as the source of a number of major river catchments in England (HR Wallingford 2012).

Regulation of water flows and flood and erosion control

Climate change is expected to lead to an intensification of the hydrological cycle (Huntington 2006), which will ultimately alter the ecohydrology of most land areas. Climate models such as the ones used for the projections reported by the IPCC include biosphere models and thus outputs provide information on how the water cycle may change in any location, though uncertainty is still high (Denman et al. 2007). According to the UKCP09 projections, likely impacts of climate change on hydrological processes in the UK include increases in winter precipitation, decreases in summer precipitation and changes to the intensity and duration of rainfall (Murphy et al. 2009).

Terrestrial water storage (groundwater, soil, lakes) and fluxes (evapotranspiration, streamflow, runoff) will be impacted by climate change, especially where precipitation tends towards extremes such as drought and intense short rainfall. Increases in temperature and potential evapotranspiration can reduce soil water content with impacts on ecosystem functions such as primary productivity or carbon cycling (Knapp et al. 2002; Christierson et al. 2012; Houle et al 2012). Ground water recharge is likely to follow seasonal patterns with low summer recharge, though uncertainty is high (Wilby et al. 2006; Jackson et al. 2011). Most, but not all, studies agree that there may be a decrease in recharge to groundwater in the UK over the next decades (Watts & Anderson 2013). Overall, research into the linkages between soil moisture and climate, as well as impact on other water stores and fluxes, is still ongoing with much uncertainty, and requires more ground observations/experimentation (Seneviratne et al. 2010; Bardgett et al. 2011).

Based on climate projections, overall runoff is expected to increase in the future in northern Europe (Milly et al. 2005; UK NEA 2011; IPCC 2014). Models of changes in river flow in the UK in response to the seasonal changes described above indicate probable reductions in summer flow and increases in winter flow, although there is still some uncertainty as reflected in differences between observations and model projections (EA 2009, 2010; Christierson et al. 2012; Hannaford & Buys 2012, Watts & Anderson 2013, Moss 2015). More frequent low summer flows will reduce supply of water; and in areas that are already water-stressed demand is likely to outstrip the supply (Vörösmarty et al. 2000; Adaptation Sub-Committee 2013; HR Wallingford 2012; IPCC 2014). On the other hand, climate induced hazards, such as floods and mudslides, are expected to increase due to climate change (Hall et al. 2003; Smith et al. 2011). The capacity of ecosystems to deliver hazard control services (flood and erosion control) will therefore become more valued with climate change.

In the UK context, flood alleviation is a priority topic. An estimated 5.2 million properties in England and 220,000 in Wales are at risk from flooding. Extreme winter flows linked to flooding have become more frequent, particularly in the west and north (Watts & Anderson 2013, Moss 2015) and flood damages have reached extreme levels in recent years (see e.g. Chatterton et al. 2010). Throughout Europe, the frequency of river flood events, and annual flood and windstorm damages, have increased over recent decades, although it is still unclear to what degree changes in climate (rather than, for example, increased exposure of valuable assets in floodplains) have contributed to these trends (IPCC 2014). There has also been increased reporting and impact from landslides type events in the UK (Smith et al. 2011).

Soil erosion in the UK has been estimated to cause an annual loss of about £9 million to the UK economy due to lost food production (EA 2004). While this sum may seem comparatively small, the total economic cost is likely to be significantly higher when costs of water treatment, sediment removal from drains and soil carbon loss are included. Increased observations of water erosion rates and occurrence have been linked to changes in agricultural practices (UK NEA 2011b). It is estimated that around one third of cropland soils in England are at moderate to very high risk of erosion (Adaptation Sub-Committee 2013).

The hazard control services that can be provided by ecosystems are influenced by the structure and composition of vegetation cover and soil properties (ProAct Network 2008, 2010). The vegetation of ecosystems such as forests and wetlands can reduce runoff, store flood water, prevent erosion, stabilise slopes, regulate stream flow and reduce storm surges. These services are already consciously used and managed in the UK and elsewhere (Coppin & Richards 1990; Morgan and Rickson 1995; Defra 2002; Grace 2002; Bullock & Acreman 2003; Mitcheli et al. 2004, Doswald and Osti 2011).

Ecosystem services for flood and erosion control may fail due to extreme pressure or when the integrity of the vegetation cover is compromised, vegetation structure/composition is changed and when the condition of the soil is altered (Smith et al. 2011). It is assumed that climate change could increase the area of land at risk of soil erosion, as well as the severity of erosion, as the intensity of precipitation events increases (Adaptation Sub-Committee 2013).

It is likely that loss of ecosystem services for flood regulation will more often occur due to land cover and land use change than as a consequence of climate change, although it may be compromised more often due to increasing extreme events. Changes of land use that frequently affect ecosystems with important functions for hazard control include installation of roads and infrastructure, including for flood protection (Hall et al. 2003, Moss 2015). Increasing extreme events in combination with other climatic and non-climatic stressors could reduce the ecosystems' capacity for buffering floods or retaining soil especially if the systems are already degraded (McHugh 2007; Palmer et al. 2009; Marchi et al. 2010). Species turnover and spread of invasives can also disrupt the water control functions. For example, *Fallopia Japonica* has had a major impact on water systems in Great Britain by exacerbating flooding or impeding water flow (Djeddour & Shaw 2010).

Pollination

Pollination is a highly important service especially for provisioning services. Pollination can be either wind or animal driven. Insects are the main vehicles of animal-driven pollination in the UK. Pollination services in the UK as well as in other parts of the world have been under stress from a variety of factors in recent decades, and severe declines have been observed (UK NEA 2011b). Wild bee diversity has decreased and insect pollinated wild plant species richness continues to decline in some areas. However, due to a lack of systematic monitoring, these trends are not fully understood. It has been suggested that climate change has already contributed to pollinator declines, alongside main drivers like landscape change, pesticide use, introduction of alien species, and pathogens and parasites (Vanbergen et al. 2013) and there are concerns that such a trend will continue (González-Varo et al. 2013). A preliminary indicator of the status of pollinating insects in the UK (Defra 2014) shows that 70 per cent of assessed bee species declined between 1980 and 2010[§].

Insect phenology and distribution can be and have been affected by changes in climate (Pelini et al. 2009). Similar impacts occur on the host plants (Cleland et al. 2007; Feehan et al. 2009). In terms of the implications of climate change for the pollination service, the interaction between plant and pollinator is crucial (Pelini et al. 2009). Asynchronous changes in phenology or distribution of plants and pollinators can disrupt pollination, especially if plant-pollinator relationships are highly species-specific (Evans & Pearce-Higgins 2012; Sparks 2012). Climate-driven mismatches in

[§] This indicator is still under development and will be refined in coming years.

phenology in the plant-pollinator relationship have been observed but climate-driven mismatches in distribution have not (Hegland et al. 2009). However, some studies suggest that such effects may arise in the future (e.g. Maes et al. 2012, Polce et al. 2014). Changes in population size will also impact pollination. Climate change impacts also indirectly affect pollination services through increases in incidence of pests and disease impacting on either host or pollinator (Le Conte & Navajas 2008; Potts et al. 2010, see also following section).

Climate change is likely to enable non-native species spread into the UK as conditions become more or less favourable for different species. Non-native plants and non-native pollinators may impact pollination services. Studies on the impact of invasive plants on pollination revealed mixed and inconclusive results (Moragues & Traveset 2005; Lopezaraiza-Mikel et al. 2007). Spread of non-native pollinators could cause competition for native pollinators though conclusive evidence is lacking; spread of disease can be a problem (Goulson 2003, 2010). However, non-native species do pollinate native plants (Goulson 2003). In the UK, many pollinators and associated hosts have declined though the causes are unknown (Biesmeijer et al. 2006). However, large-scale disruption of pollination services in the UK is highly unlikely (Smith et al. 2011) though pollination can fail in some cases (Wilcock & Neiland 2002). Plant-pollinator networks are complex, with multiple species interactions, often asymmetric, and have been shown to be relatively resilient to perturbations in many cases (Hegland et al. 2009).

Pest and disease control

Climate change affects pest and disease control services due to impacts on the distribution and abundance of pests, pathogens and disease vectors as well through impacts on their antagonists; the resulting changes in the prevalence of pests and diseases can have significant ecological and economic impacts (Pelini et al. 2009). Pests and disease vectors are likely to colonize new areas as a consequence of climate change (Capdevila-Arguelles & Zilletti 2008, EEA 2012), with potential negative impact on ecosystems and their services. It has been argued that observed rapid spread of some invasive pests or disease vectors is an indication of the high level of pest and disease control services that is normally provided by ecosystems, as the colonization success of the invasive pests and pathogens is partly attributed to the absence of an established pool of natural antagonists. Predicting the overall impact of climate change on the regulation of pests and diseases requires an integrated assessment of various factors, including the impacts of climate change on environment, hosts and antagonists (Smith et al. 2011). An overview of possible changes in pest status due to a changing climate in the UK is presented in Figure 3.

Pest	Potential changes	Consequence	Reference
Aphids	Increased number of generations per year, phenological shifts with earlier activity. Increased fecundity in some cases under elevated carbon dioxide.	Increased pesticide use e.g. prophylactic spraying for *S. avenae* control in autumn cereals to reduce Barley Yellow Dwarf Virus incidence. Increased risk of defoliation in spruce plantations e.g. green spruce aphid (*Elatobium abietinum*) in Sitka spruce.	Awmack *et al.* (1997) Evans *et al.* (2001) Holland & Oakley (2007) Harrington (2003) Zhou *et al.* (1995)
Lepidoptera			
Diamond back moth (*Plutella xylostella*); Silver Y moth (*Autographa gamma*)	Migrants that may be able to overwinter under warmer conditions.	Increased pesticide use resulting in increased resistance.	Cannon (1998)
Turnip moth (*Agrotis segetum*)	Increased survival of water-intolerant larval stages under drought conditions.	Increased pesticide use.	Collier *et al.* (2008)
European corn borer (*Ostrinia nubilalis*) Mediterranean corn borer (*Sesamia nonagrioides*)	Increased range into UK (in 2006 survey, restricted to South East England) from Europe as maize cropping increases.	Regular use of pesticides and/or adoption of insect resistant maize varieties.	Cannon (1998) Gianessi *et al.* (2003) Porter (1994)
Coleoptera			
Western corn rootworm (*Diabrotica virgifera*)	Increased range in UK with establishment from European base as maize cropping increases.	Increased pesticide use.	MacLeod *et al.* (2007)
Pollen beetle (*Meligethes aeneus*)	Earlier migration into crops.	Increased pesticide use and development of resistance (already seen on continent).	Holland & Oakley (2007)
Asian long-horn beetle (*Anoplophora glabripennis*) Southern pine beetle (*Dendroctonus frontalis*)	Warmer temperatures may allow establishment in Europe and may make UK forests susceptible.	Felling of diseased trees.	Ungerer *et al.* (1999) (modelling work from United States)
Pine weevil (*Hylobius abietis*)	Increased populations under warmer temperatures.	Death of re-stocked conifer plantations.	Broadmeadow & Ray (2005)
Thysanoptera			
Thrips	Warmer temperatures may allow establishment in UK.	Currently resistant to pyrethroids – increased pesticide use may increase resistance.	Defra (2006)
Diptera			
Cabbage root fly (*Delia radicum*)	Spring emergence earlier and less synchronized but total number of generations may not increase.	Increased pesticide use.	Holland & Oakley (2007) Collier *et al.* (1991)

Figure 3: Examples of insects which may increase in pest status in the UK (unless stated otherwise) under changing climatic conditions. *Source: Table 14.11, Chapter 14 Regulating Services, UK NEA (2011b)*

Civantos et al. (2012) modelled potential changes in pest controlling vertebrates to estimate the potential magnitude of change within Europe. Southern Europe is more likely to be affected than Northern Europe by the loss of some of the predatory controlling agents. Future changes in populations of pest controlling invertebrates depend on similar issues to other invertebrates such as availability of host/prey, phenology, and climate suitability (Thomson et al. 2010). It has been shown that, on average, a higher diversity of natural enemies strengthens pest suppression (Stiling & Cornelissen 2005; Cardinale et al. 2006).

It is predicted that incidence of disease and pests will increase under climate change, as milder winters or changes in moisture conditions facilitate the establishment or spread of harmful organisms. For example, it has been estimated that a climate warming of 2°C could allow aphids to go through five additional generation cycles per year (Yamamura & Kiritani 1998, as cited in UK NEA 2011b). However, direct observational evidence of such effects is rare. Indeed there are many confounding factors in the spread of disease and pests. In the UK, it is thought that the increased incidence of Lyme disease, which increased by over 300% between 2001 and 2010 (HPA 2012), can be attributed to climate change (Smith et al. 2011; Gilbert 2010). Increased occurrence of plant pests and disease can have serious consequences for different ecosystem services, such as pollination, food and timber production or carbon sequestration (Pelini et al. 2009; Lovett et al. 2010; Pautasso et al. 2012). As an example, sudden oak death (*Phytophthora ramorum*), an invasive pathogen, has been damaging trees in the UK since 2003, and climate change could be implicated in its spread (Brasier & Webber 2010; Sturrock et al. 2011; Grunwald et al. 2012; Pautasso et al. 2012).

It has also been shown that extreme weather events can alter the resistance of communities against invasion, if the resilience of native species is weakened (Diez et al. 2012). For example, experimental evidence in grassland found that drought decreased invasibility, while flooding increased it (Kreyling et al. 2008). Thus climate change can reduce the regulatory ecosystem services of pest and disease control.

Climate change impact on provisioning services

Terrestrial provisioning services in the UK relate mainly to food production (crops, livestock, and honey), bioenergy and timber. They are the most intensively managed type of ecosystem services in the UK. Being highly managed in an adaptive way reduces to some extent the susceptibility of the services to climate change impacts (MacKenzie-Hedger et al. 2000; Wren & Adger 2010). However, this management has impacts on other ecosystem services. Provisioning services directly depend on regulating and supporting services. Moreover, there are feedbacks between agriculture, forestry and climate change, as agriculture releases greenhouse gases (mainly N_2O and CH_4) into the atmosphere, thus exacerbating the problem, while appropriate forestry management can mitigate this through increased carbon sequestration.

As stated above, provisioning services depend more on land use decisions than on environmental parameters. Modelling of ecosystem service supply and vulnerability in Europe shows that future land use varies more with socio-economic developments than climate change (Schröter et al. 2005). The UK NEA (2011b) scenarios also show that levels of service supply change less for provisioning services than for regulating and cultural services. According to the models, change in supply of provisioning services for 2060 varies from +10% to -40%, with marginal differences in provisioning services between high and low climate change assumptions. This suggests that differences in projected changes in mean climate hardly influence provisioning services over the whole of the UK compared with other drivers, though impact may be larger at small spatial and temporal scales.

Agriculture: food and bioenergy production

Approximately 40% of land in the UK is formally under some form of agricultural production, excluding upland and semi-natural grassland grazing (Edward-Jones et al. 2011). Potential climate change impacts have been extensively studied for crops and pastures (Tubiello et al. 2007). The main underlying cause of climate change, increases in atmospheric CO_2, affects plant growth directly by stimulating photosynthesis, though interactions with temperature, rainfall and nutrient availability modulate the response of plants (Olesen & Bindi 2002; Tubiello et al. 2007; Parry et al. 2008; DaMatta et al. 2010, see also section on carbon sequestration). Changes in temperature and precipitation also impact net primary production (through phenology, metabolic rates and the length of the growing season) and quality of food, in terms of nutrient composition and fibre contents (Tubiello et al. 2007; DaMatta et al. 2010). For certain crops, therefore, climate change could result in changes (reductions or increases) in productivity as well as change in land suitability (Knox et al. 2010). However, management responses, including use of technology, can and have reduced negative impact and taken advantage of opportunities from climate change. For example, climate change has enabled and will continue to enable new crops to be grown in the UK as the climate becomes more suitable; possible examples include olives and almonds (Farming Futures 2010 a,b).

Of major concern with regard to the provisioning services, however, are extreme events, such as drought, flooding and heat stress, that may become more severe and frequent in future and are hard to address through management due to their low predictability. Indeed, the UKCIP09 projections (Murphy et al. 2009) do suggest increases in hot and/or dry summers, warm years, and a small increase in wet winters. Floods and drought have caused serious economic damage to UK agriculture in the past (Posthumus et al. 2009; Wren & Adger 2010). Changing weather conditions also impact other provisioning services such as honey production (Edward-Jones et al. 2011).

The spread of pests and diseases (see previous section) can be a serious consequence of climate change for both crops and livestock (Tubiello et al. 2007; Pilgrim et al. 2010). Indeed, disease-related impacts are likely to be among the main implications of climate change for livestock in the UK. For example, the bluetongue virus reached the UK in 2007 following its spread across Europe, presumably in part due to climate change (Szmaragd et al. 2010).

Forestry

In contrast to agriculture with its focus on annual and short-lived perennial crops, forestry is a long-term activity due to the long time required before the trees reach harvesting age. This provisioning service may therefore in the long-term be more sensitive to climate change impacts unless adaptation actions are undertaken early.

UK forestry is intensively managed and forest cover has increased in recent decades (Edward-Jones et al. 2011). The Forestry Commission has been investigating potential climate change impacts and possible adaptations; in particular usage of different species at different locations to match climate suitability (Broadmeadow et al. 2005). It is expected that climate change will affect the suitability of sites for some tree species in the UK. However, models show this is less of a problem than elsewhere in Europe, as predicted temperature increases are mostly expected to have a positive impact on forest growth except in water stressed areas (Linder et al. 2010), for example in Southern England (Hulme et al. 2002; EA 2007; Murphy et al. 2009). By contrast, extreme weather events (drought, flooding, storms) are expected to be one of the major impacts on forestry in the UK affecting yield and tree condition (Broadmeadow et al. 2009). Pest and disease outbreaks are another major concern related to climate change in this sector (see previous section). Some cases of outbreaks of pests and diseases that appear to have been triggered by climatic factors have already been observed (Edward-Jones et al. 2011; Pautasso et al. 2012).

Climate change impact on cultural services

Cultural ecosystem services are the spiritual, psychological, recreational and aesthetic non-material benefits that people derive from “nature” (MA 2005; Church et al. 2011). They are in many cases subjective and hard to define, measure and value, and vary greatly among cultures and nations. This difficulty is highlighted by the small number of cultural service indicators in use compared with other services (UNEP-WCMC 2011). Some progress has been made in the framework of the UK NEA Follow-on (UK NEA 2014) with regard to approaches for gathering information on the subconsciously held values of individuals as well as ‘shared’ values with regard to cultural ecosystem services through deliberative processes.

The UK NEA (2011b) distinguishes two broad categories of cultural services for the UK: those linked to environmental settings and those offered by wild species diversity (Figure 1). Environmental settings are grouped into types of areas where people interact with nature, i.e.

domestic gardens, local informal and formal green/blue space, nearby and wider countryside, and the country territory. An initial effort to map the potential of environmental settings to provide cultural services based on 'cultural designations' (e.g. protected area categories) and accessibility has been undertaken by Dales et al. (2014). The types of cultural services that are most often derived from wild species diversity are education and recreation (e.g. bird watching, fishing, shooting, photography). These can relate to specific species, e.g. grouse (shooting), a group of species (e.g. bird watching) or the species assemblages of whole ecosystems (e.g. nature walks).

Cultural service changes caused by climate are not easy to evaluate as they are in many cases subjective and depend on the personal experiences, 'sense of place' and preferences of the individual. For example, in terms of scenic beauty during recreation, different people might like rainy, snowy or sunny landscapes. Changes to wild species diversity are slightly easier to determine since these stem from impacts occurring on particular species and on diversity as a whole. But here as well, individuals may rate the same kinds of changes differently.

The UK NEA (2011b) scenarios show that compared with current supply of services, cultural services are expected to change vastly (and more than other ecosystem services) ranging from +40% to -59%. However, there is only marginal change in impacts on cultural services between high and low climate change projections. This suggests that differences in projected changes in mean climate hardly influence services over the whole of the UK compared with other drivers though impact may be more at small spatial and temporal scales. According to the IPCC (2014), climate change is expected to have a negative impact on cultural heritage in Europe, including many unique cultural landscapes.

Cultural services linked to environmental settings

Climate change impacts on ecosystems and biodiversity may change certain elements of the UK landscape such as structure and composition and the "look and feel" of a place though land use and management arguably play a greater role. However, some of the changes in land use triggered by climate change (e.g. changes in agricultural practices) may have a significant impact on the landscape. The most studied implications of this change are for the tourist/recreation trade though evidence is still scarce. Information on other aspects relating to cultural services (psychological, educational, spiritual and aesthetic) and climate change is very limited.

Climate is crucial to tourism and decisions of the tourist (Hamilton et al. 2005; Bigano et al. 2007). Simulation model results suggest that climate change is likely to shift holiday destinations to higher latitudes and altitudes and increase domestic holidays although population and economic growth are more important drivers (Hamilton et al. 2005). For the UK, simulation models predict that domestic holidays increase, and both domestic and international tourism may shifts northwards in the UK (Hamilton & Tol 2007, Taylor & Ortiz 2009, HR Wallingford 2012). Changes in the climate of the UK uplands are likely to bring new opportunities and attract more people towards areas that may currently be considered more marginal, which also brings risks to the environment (Orr et al. 2008).

Spread of pests and diseases in the UK might impact on the quality of the experience of the environmental setting and potentially the health of people for both UK residents and visitors (Semenza & Menne 2009; Church et al. 2011).

Climate change therefore has implications for tourism at different locations, with some areas expected to increase in value and others to decrease. Implications will also depend on actions taken by individuals to adapt to the changes. Therefore socio-economic considerations may be more important than climate change in terms of changes in tourism in the UK. This conclusion is also germane to the other cultural services relating to environmental settings engendered by ecosystems.

Cultural services linked to wild species diversity

The implication of changes in the distribution, phenology and abundance of wild species for the cultural services provided will depend on whether economic value is attached either directly or indirectly to particular species, or whether the service provides only non-material benefits. For example, a species not appearing or a new species of bird appearing produces either disappointment or excitement in bird watchers. However, the implications of this change may be increased if whole sites then either gain or lose attraction for birdwatchers due to changes in species composition, thus potentially affecting the local economy. Changes in species populations of commercial value, e.g. grouse, may have an impact on the livelihoods of those involved in the sport.

Conclusion

This review of the literature indicates that climate change, through diverse mechanisms, is likely to impact the magnitude and quality of the delivery of ecosystem services at any given location (see Table 1 below). Degree of certainty regarding the extent and direction of possible future change is low in many cases, though some services are more studied than others. For example, the literature on cultural services and climate change is still sparse, despite recently growing research interest in the topic. In many cases, climate change will not only affect the potential supply of services, but also the demand for them. This is particularly true for the regulating services, many of which can to some degree protect people from negative impacts of climate change.

Changes to water-related provisioning and regulating services due to climate change are likely to have negative impacts in the UK since demand for these services is expected to outstrip supply. However, there is still much uncertainty in model projections of water-related processes. Also, the impacts of climate change on the ability of ecosystems to provide hazard control services (such as flood protection) are a topic that requires more research, since the literature in this area covers mainly the management options to control hazards rather than the thresholds and limits of the ecosystem under climate change impacts and consequences for service delivery.

Carbon sequestration and storage and the provisioning services are the best studied, with decreases in service provision expected in some areas due to climate change impacts, and increases, especially with management, in others.

From the literature surveyed it is thought likely that the pest and disease control services of ecosystems will be of concern under climate change, although direct evidence of the influence of climate change as the instigating factor for pest or disease outbreaks is still rare.

Catastrophic failure of any ecosystem service due to climate change is unlikely unless land cover is dramatically altered such as after a fire or a flood. Land use change and degradation and associated loss of biodiversity are and are likely to continue to be the biggest threats to most ecosystem services, while climate change may exacerbate these existing pressures. However, over the long term the effects of climate change are likely to become more pronounced, and surprises in the responses and interactions of organisms and ecosystems need to be expected.

In conclusion, information relating to climate change and ecosystem services is still incomplete and often based on anecdotal evidence. Although some processes determining the impacts of climate change on ecosystems have been studied in detail (e.g. impacts on plant growth or phenology and pollination), full assessments of the implications of climate change for the supply of services are hard to achieve. This is partly due to a lack of understanding of the processes through which changes in ecosystem characteristics determine functioning and service provision, and a lack of indicators. Furthermore, the links between different services and the positive and negative feedbacks that can occur between them (Bennett et al. 2009) make it difficult to unravel potential effects of climate change. For example, the links between productivity, carbon sequestration and crop production or pest control and wild species diversity are complex and hard to capture.

Finally, the literature indicates that extreme climatic events can cause disruption to many ecosystem processes (Jentsch & Beierkuhnlein 2008) and affect service delivery. In some cases, these events may trigger long-term damage. Unfortunately, projections of future extreme events are highly uncertain, especially in terms of precipitation, and large variations exist between the projections from different models (Beniston et al. 2007; Solomon et al. 2007). Based on the current state of knowledge, there is an expectation that both the frequency of heavy rainfall events and the occurrence of summer drought will increase in the UK. Some evidence of more frequent extreme precipitation in recent years can be obtained from long-term climate data (Moss 2015). The occurrence of more frequent summer droughts is not yet confirmed by observation (Watts & Anderson 2013). More research into projections of extreme events and their short-term and long-term effects on ecosystem processes and services is necessary for managing climate change impacts.

Table 1: Overview of different climate change impacts and their effect on ecosystem services.
↓ indicates a negative effect; ↓↓ indicates a large negative effect; ↔ indicates impacts can be either negative or positive.
*Indirect impacts that are confounded by other factors.
Certainty terms (see Annex): 1 = Well established; 2 = Established but incomplete evidence; 3 = Competing explanations; 4 = Speculative

	Supporting Services		Regulation services				Provisioning Services		Cultural Services	
Climate impact	Soils and nutrient cycle	Water cycle	Carbon sequestration	Hazard control	Pollination	Pest and disease control	Agriculture	Forestry	Wild species	Environmental setting
Extreme events	↓[2]	↓↓[1]	↓↓[1]	↓↓[2]	↓[1]	↓[4]	↓↓[1]	↓↓[1]	↓[4]	↓↓[4]
Change in mean climate	↔[2]	↓[2]	↔[1]	↔[4]	↔[1]	↓[4]	↓[1]	↓[1]	↓[4]	↔[4]
Species turnover*	↔[4]	↔[2]	↔[1]	↔[4]	↔[1]	↓[4]	↔[1]	↔[1]	↔[4]	↔[4]
Spread of pests/disease*	↓[4]	↓[2]	↓[1]	↓[4]	↓[1]	↓[2]	↓↓[1]	↓↓[1]	↓[4]	↓↓[4]
Change within species (phenology, biology)	↔[4]	↔[4]	↔[1]	↔[4]	↓↓[1]	↓↓[4]	↔[1]	↔[1]	↔[4]	↔[4]

References

Adaptation Sub-Committee (2013) Managing the land in a changing climate. Progress report. Committee on Climate Change, London, UK.

Albertson, K., J. Aylen, G. Cavan, and J. McMorrow (2010) Climate change and the future occurrence of moorland wildfires in the Peak District of the UK. Climate Research, 45, 105-118.

Alonso, I., Weston, K., Gregg, R. & Morecroft, M. (2012) Carbon storage by habitat - Review of the evidence of the impacts of management decisions and condition on carbon stores and sources. Natural England Research Reports, Number NERR043.

Anderson, J.M. (1991) The effects of climate change on decomposition processes in grassland and coniferous forests. Ecological Applications, 1, 326-347.

Balvanera, P., Pfisterer, A.Ab., Buchmann, N., He, J., Nakashizuka, T., Raffaelli, D. & Schmid, B. (2006) Quantifying the evidence for biodiversity effects on ecosystem functioning and services. Ecology Letters, 9, 1146-1156.

Bardgett, R.D., Freeman, C. & Ostle, N.J. (2008) Microbial contributions to climate change through carbon cycle feebacks. The ISME Journal, 2, 805–814

Bardgett, R.D. et al. (2011) Supporting Services In: UK National Ecosystem Assessment (2011) The UK National Ecosystem Assessment: Technical Report. UNEP-WCMC, Cambridge. pp.499-534

Beniston, M., Stephenson, D.B., Christensen, O.B., Ferro, C.A.T., Frei, C., Goyete, S., Halsnaes, K., Holt, T., Jylhä, K., Koffi, B., Palutikof, J., Schöll, R., Semmler, T., Woth, K. (2007) Future extreme events in European climate: an exploration of regional climate model projections. Climatic Change, 81, 71-95.

Bennett, E.M., Cumming, G.S. & Peterson, G.D. (2005) A systems model approach to determining resilience surrogates fro case studies. Ecosystems, 8, 945-957.

Bennett, E.M., Peterson, G.D. & Gordon, L.J. (2009) Understanding relationships among multiple ecosystem services. Ecology Letters, 12, 1-11.

Biesmeijer, J.C., Roberts, S.P.M., Reemer, M., Ohlemüller, R., Rdwards, M., Peeters, T., Schaffers, A.P., Potts, S.G., Kleukers, R., Thomas, C.D., Settele, J. & Kunin, W.E. (2006) Parallel declines in pollinators and insect-pollinated plants in Britain and the Netherlands. Science, 313, 351-354.

Bigano, A., Hamilton, J. M. & Tol, R.S. J. (2007) The impact of climate change on domestic and international tourism: A simulation study. The Integrated Assessment Journal: Bridging Sciences & Policy, 7, 25-49.

Blankinship, J.C., Niklaus, A.P. & Hungate, B.A. (2011) A meta-analysis of responses of soil biota to global change. Oecologia, 165, 553-565.

Blume, H. (2011) Global Climate Change Effects on Soils. Bulletin of the Georgian National Academy of Sciences, 5, 106-112.

Boisvenue, C. & Running, S.W. (2006) Impacts of climate change on natural forest productivity – evidence since the middle of the 20th century. Global Change Biology, 12,862-882.

Braiser, C. & Webber, J. (2010) Sudden larch death. Nature, 466, 284-285.

Brevik, E. (2013) The Potential Impact of Climate Change on Soil Properties and Processes and Corresponding Influence on Food Security. Agriculture, 3, 398-417.

Broadmeadow, M.S.J., Ray, D. & Samuel, C.J.A. (2005) Climate change and the future for broadleaved tree species in Britain. Forestry, 78, 145-161.

Broadmeadow, M.S.J., Webber, J.F., Ray, D. & Berry, P.M. (2009) An assessment of the likely future impacts of climate change on UK forests. Combating climate change—a role for UK forests (eds D.J. Read, P.H. Freer-Smith, J.I.L. Morison, N. Hanley, C.C. West & P.R. Snowdon) pp. 67–98. The Stationery Office, Edinburgh.

Bullock, A. & Acreman, M. (2003) The role of wetlands in the hydrological cycle. Hydrology and Earth System Sciences, 7, 358-389.

Cao, M. & Woodward, F. (1998) Net primary and ecosystem production and carbon stocks of terrestrial ecosystems and their responses to climate change. Global Change Biology, 4, 185-198.

Capdevila-Arguelles, L. & Zilletti, B. (2008) A perspective on climate change and invasive alien species. https://secure.fera.defra.gov.uk/nonnativespecies/search.cfm

Cardinale, B.J., Srivastava, D.S., Duffy, J.E., Wright, J.P., Downing, A.L., Sankaran, M. & Jouseau, C. (2006) Effects of biodiversity on the functioning of trophic groups and ecosystems. Nature, 443, 989–992.

Cardinale, B.J., Duffy, J.E., Gonzalez, A., Hooper, D.U., Perrings, C., Venail, P., Narwani, A., Mace, G.M., Tilman, D., Wardle, D.A., Kinzig, A.P., Daily, G.C., Lareau, M., Grace, J.B., Larigauderie, A., Srivastava, D.S. & Naeem, S. (2012) Biodiversity loss and its impact on humanity. Nature, 486, 59-67.

Carey, P.D., Wallis, S., Emmett, B.A., Maskell, L.C., Murphy, J.; Norton, L.R., Simpson, I.C., Smart, S.S. (2008) Countryside Survey: UK Headline Messages from 2007. NERC/Centre for Ecology and Hydrology, Wallingford, UK.

Chapman, S.J., Bell, J., Lilly, A., Donnelly, D. (2009) Carbon stocks in Scottish peatlands. Soil Use and Management,25, 105–112.

Chatterton, J., C. Viavattene, J. Morris, E. Penning-Rowsell, S. Tapsell (2010) The Costs of the Summer 2007 Floods in England. Project: SC070039/R1, Environment Agency (EA), Bristol, UK.

Christierson, B.V., Vidal, J. & Wade, S.D. (2012) Using UKCP09 probabilistic climate information for UK water resource planning. Journal of Hydrology, 424,48-67.

Church, A., Burgess, J. & Ravencroft,N. et al. (2011) Cultural Services. In UK National Ecosystem Assessment (2011) The UK National Ecosystem Assessment: Technical Report. UNEP-WCMC, Cambridge.

Ciais,P., Reichstein, M., Viovy, N., Granier, A. Orgée,J., Allard, V., Aubinet, M., Buchmann, N., . Bernhofer, C., Carrara, A., Chevallier, F., De Noblet, N., Friend, A. D., Friedlingstein, P., Grunwald, T.Heinesch, B , Keronen, P. , Knohl, A., Krinner, G., Loustau, D., Manca, G., Matteucci, G., Miglietta, F., Ourcival, J. M. , Papale, D., Pilegaard, K. , Rambal, S., Seufert, G., Soussana, J. F., . Sanz, M. J, Schulze, E. D., Vesala, T. & Valentini, R. (2005) Europe-wide reduction in net primary productivity caused by the heat and drought in 2003. Nature, 437, 529-533.

Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., Chhabra, A., DeFries, R., Galloway, J., Heimann, M., Jones, C., Le Queré, C., Myneni, R. B., Piao, S., Thornton, P. (2014) Carbon and other biogeochemical cycles. In: Climate change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Civantos, E., Thuiller, W., Maiorano, L., Guisan, A., and Araújo, M.B. (2012) Potential impacts of climate change on ecosystem services in Europe: the case of pest control by vertebrates. BioScience, 62, 658-666.

Cleland, E.E., Chuine, I., Menzel, A., Mooney, H.A., & Swartz, M.D. (2007) Shifting plant phenology in response to global change. Trends in Ecology and Evolution, 22, 357-365.

Coppin, N. & Richards, I.G. (1990) The use of vegetation in civil engineering. Transport and road research agency, UK

Coûteaux, M., Bottner, P. & Berg, P. (1995) Litter decomposition, climate and litter quality. Trends in Ecology and Evolution, 10, 63-66.

Cranfield University (2013) National Soil Inventory Database (Topsoil data for 1983 and 1995). As cited in Adaptation Sub-Committee (2013).

Dales, N., Brown, N. & Lusardi, J. (2014) Assessing the potential for mapping ecosystem services in England based on existing habitats. Natural England Research Report NERR056

DaMatta, F.M., Grandis, A., Arenque, B.C. & Buckeridge, M.S. (Buckeridge, Marcos S.) (2010) Impacts of climate changes on crop physiology and food quality. Food Research International, 43, 1814–1823

Davidson, E.A. & Janssens, I.A. (2006) Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature, 440, 165-173

Dawson, J.J.C. & Smith, P. (2007) Carbon losses from soil and its consequences for land-use management. Science of the Total Environment, 382, 165–190.

Defra (2002) Managed Realignment Review. London, UK.

Defra (2014) Biodiversity 2020: a strategy for England's wildlife and ecosystem services. Indicators. London, UK.

Delpla, I., Jung, A.-V., Baures, E., Clement, M. & Thomas, O. (2009) Impacts of climate change on surface water quality in relation to drinking water production. Environment International, 35, 1225-1233.

Denman, K.L., Brasseur, G., Chidthaisong, A., Ciais, P., Cox, P.M., Dickson, R.E., Hauglustaine, D., Heinze, C., Holland, E., Jacomb, D., Lohmann, U., Ramachandra, S., da Silva Dias, P.L., Wofsy, S.C. & Zang, X. (2007) Couplings between changes in the climate system and biogeochemistry. In Climate Change 2007: The physical science basis. Contributions of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, UK.

De Vries, T., Bardgett, R. D. (2015) Climate change effects on soil biota in the UK. Technical Paper submitted to Natural England for the Biodiversity Report Card.

Diez, J. M., D'Antonio, C. M., Dukes, J. S., Grosholz, E. D., Olden, J. D., Sorte, C. J.B., Blumenthal, D. M., Bradley, B. A., Early, R., Ibáñez, I., Jones, S. J., Lawler, J. J. & Miller, L. P. (2012) Will extreme climatic events facilitate biological invasions? Frontiers in Ecology, 10, 249–257.

Djeddour,D.H. & Shaw, R.H. (2010) The biological control of *Fallopia Japonica* in Great Britain: Review and current status. Outlooks on pest management, 21, 15-18

Doswald, N. & Osti, M. (2011) Ecosystem-based approaches to adaptation and mitigation – good practice examples and lessons learned in Europe. BfN-Skripten 306 http://www.bfn.de/fileadmin/MDB/documents/service/Skript_306.pdf

EA (Environment Agency) (2004). The state of soils in England and Wales. Bristol, UK

EA (Environmental Agency) (2007) Areas of water stress: final classification. Environmental Agency, Bristol, UK http://publications.environment-agency.gov.uk/PDF/GEHO1207BNOC-E-E.pdf

EA (Environment Agency) (2009) Investing for the future. Flood and coastal risk management in England: a long term strategy. Bristol, UK http://cdn.environment-agency.gov.uk/geho0609bqdf-e-e.pdf

Edward-Jones, G. et al. (2011) Provisioning Services. In UK National Ecosystem Assessment (2011b) The UK National Ecosystem Assessment: Technical Report. UNEP-WCMC, Cambridge. pp.597-632

EEA (2012) The impacts of invasive alien species in Europe. EEA Technical report No 16/2012, Copenhagen, Denmark.

Elmqvist, T., Folke, C., Nystrom, M., Peterson, G., Bengtsson, J., Walker, B., Norberg, J. (2003) Response diversity, ecosystem change, and resilience. *Frontiers in Ecology and the Environment* 1, 488-494.

Emmett, B.A., Beier, C., Estiarte, M., Tietema, A., Kristensen, H.L., Willimas, D., Penuelas, P., Schmidt, I. & Sowerby, A. (2004) The response of soil processes to climate change: results from manipulation studies of shrublands across and environmental gradient. Ecosystems, 7, 625-637.

Evans, K. & Pearce-Higgins, J. (2012) Mechanisms driving UK biodiversity responses to climate change: assessment and indicators. Technical Paper submitted to Natural England for the Biodiversity Report Card.

Farming Futures (2010a) General opportunities and challenges. Climate change series. Factsheet 2. http://www.farmingfutures.org.uk/sites/default/files/casestudy/pdf/opportunities_and_challenges.pdf

Farming Futures (2010b) Focus on olives. Climate change series. Case Study 8. http://www.farmingfutures.org.uk/sites/default/files/casestudy/pdf/Mark_Diacon_CS8_WEB.pdf

Feehan, J., Harley, M. & van Minnen, J. (2009) Climate change in Europe 1: Impact on terrestrial ecosystems and biodiversity. A review. Agronomy for Sustainable Development, 29, 409-421.

Fenner, N. & Freeman, C. (2011) Drought-induced carbon loss in peatlands. Nature Geoscience, 4, 895-900.

Finch, J.W. (2000) Modelling the soil moisture deficits developed under grass and deciduous woodland: the implications for water resources. Journal of the Chartered Institution of Water and Environmental Management, 14, 371–376.

FLUF (Foresight Land Use Future) (2010) Making the most of land in the 21st century: final report. The Government Office for Science, London.

Ge, Z., Kellomäki, S., Peltola, Zhou, X., Väisänen, H.,Stradman, H. (2012) Impacts of climate change on primary production and carbon sequestration of boreal Norway Spruce forests: Finland as a model. Climatic Change, DOI: 10.1007/s10584-012-0607-1

Gerten, D., Schaphoff, S., Haberlandt, U., Lucht, W. & Stich, S. (2004) Terrestrial vegetation and water balance – hydrological evaluation of a dynamic global vegetation model. Journal of Hydrology, 286, 249-270.

Gilbert, L. (2010) Altitudinal patterns of tick and host abundance: a potential role for climate change in regulating tick-borne diseases. Oecologia, 162, 217-225

González-Varo, J. P., Biesmeijer, J. C., Bommarco, R., Potts, S. G., Schweiger, O., Smith, H. G., Steffan-Dewenter, I., Szntgyörgyi, H., Woyciechowski, M. & Vilà, M. (2013) Combined effects of global change pressures on animal-mediated pollination. Trends in Ecology & Evolution, 28(9), 524-530.

Goulson, D. (2003) Effects of introduced bees on native ecosystems. Annual Review of Ecological and Evolutionary Systems, 34, 1-26

Goulson, D. (2010) Impact of non-native bumblebees in Western Europe and North America. Applied Entomological Zoology, 45, 7-12

Grace, J.M. (2002) Effectiveness of vegetation in erosion control from forest road side slopes. Transactions of the ASAE, 45, 681-685.

Grünwald, N. J. , Garbeletto, M., Gross, E.M., Heugens, K. & Prospero, S. (2012) Emergence of the sudden oak death pathogen *Phytophthora ramorum*. Trends in Microbiology, 20, 131-138.

Haines-Young, R. et al. (2011) The UK NEA Scenarios : development of storylines and analysis of outcomes. In UK National Ecosystem Assessment (2011) The UK National Ecosystem Assessment: Technical Report. UNEP-WCMC, Cambridge. pp. 1195-1264.

Hall, J.W., Evans, E.P., Penning-Roswell, E.C., Sayers, P.B., Thorne, C.R. & Saul, A.J. (2003) Quantified scenarios analysis of drivers and impacts of changing flood risk in England and Wales: 2030-2100. Environmental Hazards, 5, 51-65.

Hamilton, J.M., Maddison, D.J. & Tol, R.S.J. (2005) Effects of climate change on international tourism. Climate Research, 29, 245-254.

Hamilton, J.M. & Tol, R.S.J. (2007) The impact of climate change on tourism in Germany, the UK and Ireland: a simulation study. Regional Environmental Change, 7, 161-172.

Hannaford, J.; Buys, G. (2012) Trends in seasonal river flow regimes in the UK. Journal of Hydrology, 475. 158-174.

Hegland, S.J., Nielsen, A., Lázaro, A., Bjerknes, A-L. & Totland, Ø. (2009) How does climate affect plant-pollinator interactions? Ecology Letters, 12, 184-195.

Heimann, M. & Reichstein, M. (2008) Terrestrial ecosystem carbon dynamics and climate feedbacks. Nature, 451, 289-292.

Hicks, C., Woroniecki, S., Fancourt, M., Bieri, M., Garcia Robles, H., Trumper, K., Mant, R., (2014) The relationship between biodiversity, carbon storage and the provision of other ecosystem services: Critical Review for the Forestry Component of the International Climate Fund. Cambridge, UK.

Houle, D., Bouffard, A., Duchesne, L., Logan, T., and Harvey R. 2012. Projections of future soil temperature and water content for three southern Quebec forested sites. Accepted in Journal of Climate

HPA (Health Protection Agency) (2012) Epidemiology of Lyme borreliosis in the UK. http://www.hpa.org.uk/Topics/InfectiousDiseases/InfectionsAZ/LymeDisease/EpidemiologicalData/lymLymeepidemiology/ Retrieved 21/08/2012.

HR Wallingford (2012) The UK Climate Change Risk Assessment 2012. Evidence Report. Defra, London, UK.

Hulme, M., Jenkins, G.J., Lu, X., Turnpenny, J.R., Mitchell, T.D., Jones, R.G., Lowe, J., Murphey, J.M., Hassell, D., Boorman, P., McDonald, R. & Hill, S. (2002) Climate change scenarios for the United Kingdom: The UKCIP02 Scientific Report. Tyndell Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich, UK.

Huntington, T.G. (2006) Evidence for intensification of the global water cycle: review and synthesis. Journal of Hydrology, 319, 83-95.

Huxman, T.E., Wilcox, B.P., Breshears, D.D., Scott, R.L., Snyder, K.A., Small, E.E., Hultine, K., Pockman, W.T. & Jackson, R. B. (2005) Ecohydrological implications of woody plant encroachment. Ecology, 86, 308-319.

IPCC (2007) Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Parry, M.L., Canziani, O.F., Palutikof, J., van der Linden, P.J., and Hanson, C.E. Cambridge University Press, Cambridge, UK. -976pp.

IPCC (2013) Climate change 2013: the Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, NY, USA.

IPCC (2014) Climate Change 2014: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on

Climate Change, Cambridge University Press, Cambridge, UK and New York, NY, USA.

Isbell, F., Calcagno, V., Hector, A., Connolly, J., Harpole, W.S., Reich, P.B., Scherer-Lorenzen, M., Schmid, B., Tilman, D., Van Ruijven, J., Weigelt, A., Wilsey, B.J., Zavaleta, E.S., Loreau, M. (2011) High plant diversity is needed to maintain ecosystem services. Nature, 477, 199-202.

Jackson, J., Li, Y., Murrells, T., Passant, N., Sneddon, S., Thomas, J., Thistlethwaite, G., Dyson, K. & Cardenas, L. (2009) Greenhouse Gas Inventories for England, Scotland, Wales and Northern Ireland: 1990–2007 AEAT/ENV/R/2873.

Jackson, C.R., Meister, R. & Prudhomme, C. (2011) Modelling the effects of climate change and its uncertainty on UK Chalk groundwater resources from an ensemble of global climate model projections. Journal of Hydrology, 399, 12-28.

Jentsch, A. & Beierkuhnlein, C. (2008) Research frontiers in climate change: effects of extreme meteorological events on ecosystem. Geoscience, 340, 621-628.

JNCC (2011) Towards an assessment of the state of UK peatlands. JNCC report No 445

Kardol, P., Cregger, M.A., Campany, C.E. & Classen, A.T. (2010) Soil ecosystem functioning under climate change: plant species and community effects. Ecology, 91, 767-781.

Kirschbaum, M.U.F. (1995) The temperature dependence of soil organic matter decomposition, and the effect of global warming on soil organic C storage. Soil Biology and Biochemistry, 27, 753-760.

Knapp, A.K., Fay, P.A., Blair, J.M., Collins, S.L., Smith, M.D., Carlisle, J.D., Harper, C.W., Danner, B.T., Lett, M.S. & McCarron, J.K. (2002) Rainfall variability, carbon cycling and plant species diversity in a mesic grassland, Science, 298, 2202-2205

Knox, J., Morris, J. & Hess, T. (2010) Identifying future risks to UK agricultural crop production: putting climate change in context. Outlook on Agriculture, 39, 249-256.

Kremen, C. (2005) Managing ecosystem services: what do we need to know about their ecology? Ecology Letters, 8, 468-479.

Kreyling, J., Beierkuhnlein, C., Ellis, L. & Jentsch, A. (2008) Invasibility of grassland and heathland communities exposed to extreme weather events – additive effects of diversity resistance and fluctuating physical environment. Oikos, 117, 1542-1554.

Le Conte, Y. & Navajas, M. (2008) Climate change : impact on honey bee populations and diseases. Revue Scientifique et Technique (International Office of Epizootics), 27, 499-510

Linder, M., Maroschek, M., Netherer, S., Kremer, A., Barbati, A., Garcia-Gonzalo, J., Seidi, R., Delzon, S., Corona, P., Kolström, M., Lexer, M.J. & Marchetti, M. (2010) Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. Forest Ecology and Management, 259, 698-709.

Lopezaraiza-Mikel, M.E., Hayes, R.B., Whalley, M.R. & Memmott, J. (2007) The impact of an alien plant on a native pollinator network: an experimental approach. Ecology Letters, 10, 539-550.

Lovett, G. M., Arthur, M. A., Weathers, K. C., & Griffin, J. M. (2010). Long-term changes in forest carbon and nitrogen cycling caused by an introduced pest/pathogen complex. Ecosystems,13, 1188–1200

MacCarthy, J., Thomas, S., Choudrie, S., Passant, N.,Thistlethwaite, G., Murrells, T., Watterson, J., Cardenas, L. & Thomson, A. (2010) UK Greenhouse Gas Inventory, 1990 to 2008: Annual Report for submission under the Framework Convention on Climate Change AEAT/ENV/R/2978.

Mace, G.M., Norris, K. & Fitter, A.H. (2012) Biodiversity and ecosystem services: a multilayered relationship. Trends in Ecology and Evolution, 27, 19-26.

Maes, J., Hauck, J., Paracchini, M.L., Ratamäki, O., Termansen, M., Perez-Soba, M., Kopperoinen, L., Rankinen, K., Schägner, J., Henrys, P., Cisowska, I., Zandersen, M., Jax, K., La Notte, A., Leikola, N., Pouta, E., Smart, S., Hasler, B., Lankia, T., Andersen, H.E., Lavalle, C., Vermaas, T., Hussen Alemu, M., Scholefield, P., Batista, F., Pywell, R., Hutchins, M., Blemmer, M., Fonnesbech-Wulff, A., Vanbergen, A.J., Münier, B., Baranzelli, C., Roy, D., Thieu, V., Zulian, G., Kuussaari, M., Thodsen, H., Alanen, E., Egoh, D., Sørensen, P.B., Braat, L., Bidoglio, G. (2012) A spatial assessment of ecosystem services in Europe: methods, case studies and policy analysis - phase 2. Synthesis report. PEER Report No 4. Ispra: Partnership for European Environmental Research

Marchi, L., Borga, M., Preciso, E. & Gaume, E. (2010) Characterisation of selected extreme flash floods in Europe and implications for flood risk management. Journal Hydrology, 394, 118-133.

McCarthy HR, Oren R, Johnsen KH, Gallet-Budynek A, Pritchard SG, Cook CW, LaDeau SL, Jackson RB, Finzi AC (2010) Re-assessment of plant carbon dynamics at the Duke free-air CO2 enrichment site: interactions of atmospheric [CO2] with nitrogen and water availability over stand development. New Phytologist, 185, 514–528

McHugh, M. (2007) Short-term changes in upland soil erosion in England and Wales: 1999 to 2002. Geomorphology, 86(1-2), 204-213.

McKenzie-Hedger, M., Gawith, M., Brown, I., Connell, R., Downing, T.E. (eds) (2000) Climate change: assessing impacts – identifying reponses. The first three years of the UK Climate Impacts Programme. UKCIP Technical Report, UKCIP, Oxford.

Miles, L., Dunning, E., Doswald, N., Osti, M. 2010. A safer bet for REDD+: Review of the evidence on the relationship between biodiversity and the resilience of forest carbon stocks. Working Paper v2. *Multiple Benefits Series* **10**. Prepared on behalf of the UN-REDD Programme. UNEP World Conservation Monitoring Centre, Cambridge, UK.

Millennium Ecosystem Assessment (2005) Millennium ecosystem assessment: ecosystems and well-being. Synthesis. Island Press, Washington, DC

Milly, P.C.D., Dunne, K.A. & Vecchia, A.V. (2005) Global pattern of trends in streamflow and water availability in a changing climate. Nature, 438, 347-350.

Mitcheli, E.R., Kirchner, J.W. & Larsen, E.W. (2004) Quantifying the effect of riparian forest versus agricultural vegetation on river meander migration rates, central Sacramento river, California, USA. River Research Application, 20, 537-548

Montoya, J.M. & Raffaelli, D. (2010) Climate change, biotic interactions and ecosystem services. Philosophical Transactions of the Royal Society: B, 365, 2013-2018.

Mooney, H., Larigauderie, A., Cesario, M., Elmquist, T., Hoegh-Guldberg, O., Lavorel, S., Mace, G.M., Palmer, M., Scholes, R., & Yahara, T. (2009) Biodiversity, climate change, and ecosystem services. Current Opinion in Environmental Sustainability, 1, 46-54.

Morgan, R.P.C. & Rickson, R.J. (eds) (1995) Slope stabilisation and erosion control: a bioengineering approach. Chapman and Hall, London, UK

Moragues, E. & Traveset, A. (2005) Effect of *Carpobrotos* spp. on the pollination success of native plant species in the Balearic Islands. Biological Conservation, 122,611-619

Moss, B. (2015) Freshwaters, climate change and UK conservation. Technical Paper submitted to Natural England for the Biodiversity Report Card.

Murphy, J.M., Sexton, D.M.H., Jenkins, G.J., Boorman, P.M., Booth, B.B.B., Brown, C.C., Clark, R.T., Collins, M., Harris, G.R., Kendon, E.J., Betts, R.A., Brown, S.J., Howard, T. P., Humphrey, K. A., McCarthy, M. P., McDonald, R. E., Stephens, A., Wallace, C., Warren, R., Wilby, R., Wood, R. A. (2009), UK Climate Projections Science Report: Climate change projections. Met Office Hadley Centre, Exeter.

Natural England (2010) England's peatlands: carbon storage and greenhouse gases. Project report. Project NE257.

Norris, K. et al. (2011) Biodiversity in the context of ecosystem services. In UK National Ecosystem Assessment (2011) The UK National Ecosystem Assessment: Technical Report. UNEP-WCMC, Cambridge. Pp.63-104

Olesen, J.E. & Bindi, M. (2002) Consequences of climate change for European agricultural productivity, land use and policy. European Journal of Agronomy, 16, 239-262.

Orr, H.G., Wilby, R.L., Hedger, M.M. & Brown, I. (2008) Climate change in the uplands: a UK perspective on safeguarding regulatory ecosystem services. Climate Research, 37, 77-98.

Ostle, N.J., Levy, P.E., Evans, C.E., Smith, P. (2009) UK land use and soil carbon sequestration. Land Use Policy, 26S, S274–S283.

Palmer, M., A., Lettenmaier, D.P., Poff, N. L., Postel, S.L., Richter, B. & Warner, R. (2009) Climate change and river ecosystems: protection and adaptation options. Environmental Management, 44, 1053-1068.

Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J. & Hanson, C.E. (eds) (2008) Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007. Cambridge University Press, Cambridge.

Pautasso, M., Döring, T.F., Garbelotto, M., Pellis, L. & Jeger, M.J. (2012) Impacts of climate change on plant diseases – opinions and trends. European Journal of Plant Pathogens, 133, 295-313.

Pelini, S.L., Prior, K.M., Parker, D.J., Dzurisin, J.D.K., Lindroth, R.L. & Hellmann, J.J. (2009) Climate change and temporal and spatial mismatches in insect communities. In

Letcher, T. (ed) Climate change: observed impacts on planet earth. Elsevier, Oxford, UK.

Pilgrim, E.S., Macleod, C.J.A., Blackwell, M.S.A., Bol, R., Hogan, D.V., Chadwick, D.R., Cardenas, L., Misselbrook, T.H. Haygarth, P.M., Brazier, R.E., Hobbs, P., Hodgson, C., Jarvis, S., Dungait, J., Murray, P.J. & Firbank, L.G. (2010). Interactions among agricultural production and other ecosystem services delivered from European temperate grassland systems. Advances in Agronomy 109, 117–154.

Polce, C., Garratt, M.P., Termansen, M., Ramirez-Villegas, J., Challinor, A.J., Lappage, M.G., Boatman, N.D., Crowe, A., Endalew, A.M., Potts, S.G., Somerwill, K.E. and Biesmeijer, J.C. (2014) Climate-driven spatial mismatches between British orchards and their pollinators: Increased risks of pollination deficits. Global Change Biology, 20 (9). 2815 - 2828.

Posthumus, H., Morris, J., Hess, T.M., Neville, D., Philips, E. & Baylis, A. (2009) Impacts of the summer 2007 floods on agriculture in England. Journal of Flood Risk Management, 2, 182-189.

Potts, S.G., Biesmeijer, J.C., Kremen, C., Neumann, P., Schweiger, O. & Kunin, W.E. (2010) Global pollinator declines: trends, impacts and drivers. Tends in Ecology and Evolution, 25, 345-353.

Pritchard, S.G. (2011) Soil organisms and global climate change. Plant pathology, 60, 82-99.

ProAct Network (2008) The role of environmental management and eco-engineering in disaster risk reduction and climate change adaptation.

ProAct Network (2010) Maximising ecosystem services for disaster risk reduction

Pussinen A, Nabuurs GJ, Wieggers HJJ, Reinds GJ, Wamelink GWW, Kros J, Mol-Dijkstra JP, de Vries W (2009) Modelling long-term impacts of environmental change on mid- and high-latitude European forests and options for adaptive forest management. Forest Ecological Managment, 258, 1806–1813Schröter, D. et al. (2005) Ecosystem supply and vulnerability to global change in Europe. Science, 310, 1333-1337

Semenza, J.C. & Menne, B. (2009) Climate change and infectious diseases in Europe. The Lancet, 9, 365-375.

Seneviratne, S.I., Corti, T., Davin, E.L., Hirschi, M., Jaeger, E.B., Lehner, I., Orlowsky, B., Teuling, A.J. (2010) Investigating soil moisture-climate interactions in a changing climate: a review. Earth Science Reviews, 99, 125-161.

Smith, J. U.; Chapman, S. J.; Bell, J. S.; Bellarby, Jessica; Gottschalk, P.; Hudson, G.; Lilly, A.; Smith, P.; Towers, W. (2009) Developing a methodology to improve Soil C Stock Estimates for Scotland and use of initial results from a resampling of the National Soil Inventory of Scotland to improve the Ecosse Model : Final Report. The Scottish Government, Edinburgh, UK.

Smith, P. et al. (2011) Regulating Services. In UK National Ecosystem Assessment (2011) The UK National Ecosystem Assessment: Technical Report. UNEP-WCMC, Cambridge. pp. 535-596

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. & Miller, H.L. (eds.) (2007) Climate Change 2007: The Physical Science Basis. Contribution of

Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007. Cambridge University Press, Cambridge, UK.

Sowerby, A., Emmett, B.A., Tietema, A., Beier, C., 2008. Contrasting effects of repeated summer drought on soil carbon efflux in hydric and mesic heathland soils. Global Change Biology 14, 2388–2404.

Sparks, T. (2012) Implications of climate change for phenology in the UK. Technical Paper submitted to Natural England for the Biodiversity Report Card.

Stiling, P., Cornelissen, T. (2005) What makes a successful biocontrol agent? A meta-analysis of biological control agent performance. Biological Control 34 (2005) 236–246.

Sturrock, R. N., Frankel, S. J., Brown, A. V., Hennon, P. E., Kliejunas, J. T., Lewis, K. J., Worrall, J. J. & Woods, A. J. (2011) Climate change and forest diseases. USDA Forest Service / UNL Faculty Publications. Paper 143. http://digitalcommons.unl.edu/usdafsfacpub/143

Szmaragd, C., Wilson, A.J., Carpenter, S., Wood, J.L.N., Mellor, P.S. & Gubbins, S. (2010) The Spread of Bluetongue Virus Serotype 8 in Great Britain and Its Control by Vaccination. PLoS One, 5, e9353.

Taylor, T., Ortiz, R. A. (2009) Impacts of climate change on domestic tourism in the UK: a panel data estimation. Tourism Economics, 15(4), 803-812.

Thompson, I., Mackey, B., McNulty, S., Mosseler, A. (2009) Forest Resilience, Biodiversity, and Climate Change. A synthesis of the biodiversity/resilience/stability relationship in forest ecosystems. Technical Series No. 43. Secretariat of the Convention on Biological Diversity, Montreal

Thomson, L.J., MacFayden, S. & Hoffmann, A.A. (2010) Predicting the effects of climate change on natural enemies of agricultural pests. Biological Control, 52, 296-306.

UK National Ecosystem Assessment (2011a) The UK National Ecosystem Assessment: Synthesis of the key Findings. UNEP-WCMC, Cambridge.

UK National Ecosystem Assessment (2011b) The UK National Ecosystem Assessment: Technical Report. UNEP-WCMC, Cambridge.

UK National Ecosystem Assessment (2014) The UK National Ecosystem Assessment Follow-on: Synthesis of Key Findings. UNEP-WCMC, LWEC, UK.

UNEP-WCMC (2011) Developing ecosystem service indicators: Experiences and lessons learned from sub-global assessments and other initiatives. CBD Technical Series No 58. Secretariat of the Convention on Biological Diversity, Montreal, Canada.

Vanbergen, A. J., Baude, M., Biesmeijer, J. C., Britton, N. F., Brown, M. J. F., Bryden, J., Budge, G. E., Bull, J. C., Carvell, C., Challinor, A. J., Connolly, C. N., Evans, D. J., Feil, E. J., Garratt, M. P., Greco, M. K., Heard, M. S., Jansen, V. A. A., Keeling, M. J., Kunin, W. E., Marris, G. C., Memmott, J., Murray, J. T., Nicolson, S. W., Osborne, J. L., Paxton, R. J., Pirk, C. W. W., Polce, C., Potts, S. G., Priest, N. K., Raine, N. E., Roberts, S., Ryabov, E. V., Shafir, S., Shirley, M. D. F., Simpson, S. J., Stevenson, P. C., Stone, G. N., Termansen, M. and Wright, G. A. (2013) Threats to an ecosystem service: pressures on pollinators. Frontiers in Ecology and the Environment 11, 251-259.

Vörösmarty, C.J., Green, P., Salisbury, J., Lammers, R.B. (2000) Global water resources: vulnerability from climate change and population growth. Science, 289, 284-288.

Waldrop, M.p. & Firestone, M.K. (2006) Response of microbial community composition and function to soil climate change. Microbial ecology, 52, 716-724

Watts, G. & Anderson, M. (eds.) (2013) A climate change report card for water. LWEC report card.

Wilby, R.L., Whitehead, P.G., Wade, A.J., Butterfield, D., Davis, R.J. & Watts, G. (2006) Integrated modelling of climate change impacts on water resources and quality in a lowland catchment: River Kennet, UK. Journal of Hydrology, 330, 204-220.

Wilcock, C. & Neiland, R. (2002) Pollination failure in plants: why it happens and when it matters. Trends in Plant Science, 7, 270-277.

Worrall, F., Chapman, P., Holden, J., Evans, C., Artz, R., Smith, P. & Grayson, R. (2010) Peatlands and climate change. Scientific review. IUCN

Worrall, F., Chapman, P., Holden, J., Evans, C., Artz, R., Smith, P. & Grayson, R. (2011) A review of current evidence on carbon fluxes and greenhouse gas emissions from UK peatland. JNCC Report, No. 442.

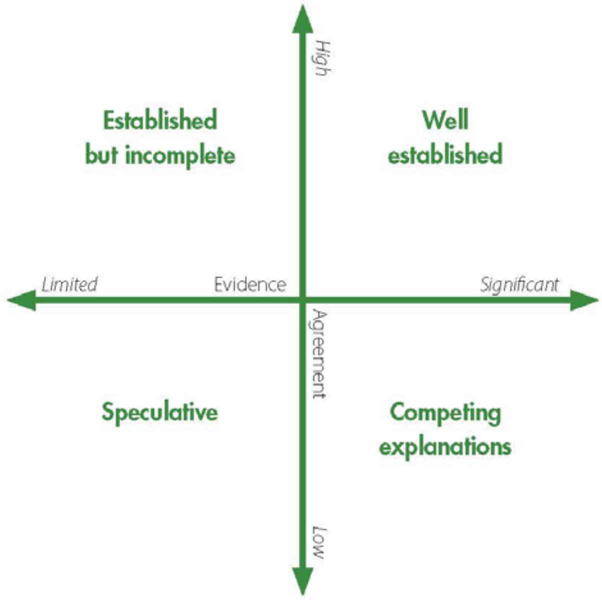
Wreford, A. & Adger W. N. (2010) Adaptation in agriculture: historic effects of heat waves and droughts on UK agriculture, International Journal of Agricultural Sustainability, 8, 278-289.

Zhao, M. & Running, S. W. (2010) Drought induced reduction in global terrestrial net primary production from 2000-2009. Science, 329, 940-943.

Annex

Uncertainty terms used in the key findings as drawn from the UK NEA (2011a)

1. *Well established:* high agreement based on significant evidence
2. *Established but incomplete evidence:* high agreement based on limited evidence
3. *Competing explanations:* low agreement, albeit with significant evidence
4. *Speculative:* low agreement based on limited evidence



a. *Virtually certain:* >99% probability of occurrence
b. *Very likely:* >90% probability
c. *Likely:* >66% probability
d. *About as likely as not:* >33-66% probability
e. *Unlikely:* <33% probability
f. *Very unlikely:* <10% probability
g. *Exceptionally unlikely:* <1% probability

Certainty terms 1 to 4 constitute the 4 box model, while a to g constitute the likelihood scale.